Was there a 1930's Meltdown of Greenland Glaciers?

A Senior Thesis

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by

Adam Herrington

Project Advisor: Professor Jason E. Box, Department of Geography

Approved by

Anne E. Carey

Dr. Anne E. Carey, Academic Advisor

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Abstract Warming around Greenland (1994-2007) has been implicated in widespread glacier recession observed by satellite sensors. To better understand if the recent glacier behavior is abnormal, we use maps, photos, and documentary data from 20th century expedition reports to document if similar glacier response occurred during an analogous warm period beginning in the 1920s. Analyzed together with existing published data, I find that the years containing the greatest proportion of retreating land terminating glaciers over a 90 year record (1870-1960) were 1920-1940 and that of marine terminating glaciers were 1930-1950 over a 140 year record (1850-1990). Furthermore, four marine terminating length change records show rapid length changes concurrent with anomalously high annual air temperatures, all occurring between 1923 and 1946. Thus, the recent precisely-documented Greenland glacier recession can be regarded as a case of a highly sensitive system useful in indicating climate change.

Introduction

It had been conventional thought among glaciologist that ice sheet sensitivity to climate operates only on time scales of centuries to millennia. In recent years, that thinking has been turned on end as major Greenland ice sheet outlet glaciers increased greatly in flow speed and ice discharge rate (e.g. Rignot and Kanagaratnam, 2006) with the largest outlets accelerating in excess of a factor of two (e.g. Joughin et al. 2004; Stearns and Hamilton, 2005; Howat et al. 2007) concurrent with a warming climate. Discovery of potentially sensitive ice sheet response to climate warming brought global sea level rise into focus for millions of people globally, signaling the need for an urgent reduction in greenhouse gas emissions and a dramatic change in energy policy. Recent warming, however, is not without precedent. Greenland coastal temperature records (Figure 1) indicate a 1920s decadal warming rate 1.5 times the recent 1995-2005 rate (Chylek et al., 2006; Box et al. 2009), ushering in the two warmest decades on the coastal station records, the 1930s and 1940s (Cappelen et al. 2007; Box, 2002).

Despite the wealth of recent observations suggesting enhanced ice sheet sensitivity to climate, very few studies have examined how the Greenland ice sheet may have responded to the abrupt 1920s warming. Recent warming has been attributed to the observed increase in the rate of retreat of Greenland glaciers during the period 2000-2006 relative to the 1992-2000 period (Moon and Joughin, 2008), thus a similar response may be expected during the 1920s. An extensive compilation of glacier front positions from west Greenland by Weidick (1959, 1968, 1994) illustrated a history of glacial extent consisting of a maximum between 1850 and 1880, followed by a period of recession until the 1960s and a general readvance occurring thereafter until the 1980s. Weidick (1995) elaborated on his analysis by stating that the main period of recession of west Greenland was between 1920 and the 1950s, indicating an enhanced retreat in response to the 1920s warming period. In addition, more recent work suggests that surface meltwater production and extent in the 1920s and 1930s were among the greatest during the past century (Fettweis et al. 2008; Knappenberger et al. *in review*).

This work aims to provide broader context for the role of climate in ice sheet sensitivity by testing the hypothesis: *there was an accelerated retreat of Greenland glaciers in response to the 1920s warming period*. In contrast to the work by Weidick

(1959, 1968, 1994, 1995) indicating an enhanced recession of Greenland glaciers between 1920 and the 1950s, this work investigates the timing and magnitude of the retreat relative to the trend of warming between 1920 and 1950. I will test my hypothesis by creating a database of Greenland glacier length changes and comparing the length change trends with the meteorological records of Greenland.

Data

Prior to the launch of the Corona spy satellite in 1959, aerial and terrestrial photographs, maps, paintings, written accounts and glaciological studies are the only available observations of Greenland glaciers. The earliest known scientific studies of glaciers were carried out by Heinrich J. Rink in the mid 19th century (Weidick and Bennike, 2007). Systematic coastline mapping began in the late 19th century (e.g. German Ryder Expedition of 1892) and increased in the 1930s when expeditions first began utilizing planes for aerial photography (e.g. British Arctic Air Route Expedition of 1930/31 (Watkins et al. 1932)). Sources of glacier position data used in this study are tabulated in Table 1.

The different sources used to determine a glacier's frontal position are subject to various degrees of uncertainty. The difficulty of performing a meaningful error analysis has led to the assumption in this study that all data sources are accurate unless otherwise shown. Confirmed mapping errors are documented. For example, inaccurate mapping during the Second Thule Expedition led Lauge Koch to mistaken compacted tabular icebergs as an ice shelf extending close to the mouth of the Victoria Fjord, North Greenland (Koch, 1928). Such large mapping errors are probably rare in this dataset, and errors of a lesser magnitude (e.g. measurement errors) are likely to be more prevalent. As discussed later, the data will be presented in a way that minimizes these errors.

Methods

Usually, the most easily determined metric for a change in a glaciers shape is a change in glacier length. Although other metrics such as surface velocity and thickness may be more desirable for studying links between glaciers and climate, they are less readily determined nor available for the early to mid 20th century. We expect that interpretation of the length change time series will be most problematic for marine terminating glaciers since their force balance is not likely to be described by the shallow ice approximation (Patterson, 1999). The very different stress regime of marine relative to land glaciers can result in advance or retreat of the calving front that may be at best, indirectly related to climate (Meier and Post, 1987; Pfeffer, 2007).

I have constructed a time series of length changes for 77 Greenland glaciers. The typical temporal resolution for an individual glacier in our sample is roughly five terminus positions per century. The average temporal resolution of this time series is therefore too coarse to allow determination of the response of our sample to a decadal warming rate. A few individual glacier records do offer the temporal resolution necessary to infer a relationship to the 1920-1930 decadal rate of warming, and will be used to test my hypothesis. However, sample averages remain useful in determining whether the general patterns of length changes in Greenland are related to longer term climate trends in Greenland.

To determine the status of all glaciers in our sample in any given year, it is necessary to approximate annual resolution for each glacier. Each glacier has N terminus positions during N snap shots in time mined from the Table 1 sources and the entire database is tabulated in the Table 2. To approximate an annual resolution spanning the earliest and most recent terminus positions for any glacier, we simply interpolate on the time series, that is, we assume a constant annual rate of length change between any two temporally adjacent observations on a glacier. This approximation is less valid for marine terminating glaciers since their calving fronts exhibit abrupt fluctuations that can exceed the length change between two temporally adjacent observations in our dataset (e.g. Sohn et al. 1998).

To minimize errors associated with interpolation, time series of the proportion of glaciers in our sample retreating in a given year was constructed (Figures 2a & 2b). This method considers only the sign, not the magnitude of the glacier terminus position change. I also attempt to minimize uncertainty by separating the database among land and marine terminating glaciers. The expected distinction between marine and land terminating glaciers is indicated by the standard deviation of the mean annual length change of marine glaciers being roughly three times that of land terminating glaciers.

Four individual records of length change do offer the temporal resolution necessary to test my hypothesis of accelerated glacial retreat in response to the 1920s warming. These records of length change consist of about 12 terminus positions per century, roughly twice the resolution of the bulk sample. Still, I interpolated between temporally adjacent observations to approximate annual length changes. Multiplication of each glacier's length change time series by its corresponding width, measured as the average width over a glacier's length change record, further defines the magnitude of glacier change. To compare a glacier's annual area change to the climate of Greenland, I normalized the meteorological station surface air temperature records to the resolution of an individual glacier's area change record. For example, if a glacier's frontal position was determined in 1910 and 1920, then after computing the rate of area change between these two years, I compute the average annual surface air temperature between these same two years from the closest meteorological station spanning the glaciers time series (see Figure 3). Recalling that our goal is to test the hypothesis that *there was an accelerated retreat of Greenland glaciers in response to the 1920s warming period*, I then examine the correlation between the temperature and area change.

Results and Discussions

Land Terminating Glaciers

The 24 land terminating glaciers of the database are all located in southwest Greenland and the proportion of these glaciers retreating over time is shown in Figure 2a. The land terminating glaciers time series begins with an abrupt 30% increase in the proportion of glaciers retreating during the last two decades of the 19th century followed by an approximately linear increase until about 1940, where roughly 80% of the glaciers were in retreat. Beginning in the 1940s, the sample demonstrates an abrupt reduction in occurrence of retreat until the end of the time series in 1960,

The proportion of land terminating glaciers retreating over time is likely caused by the local climate trends of the sample. The sample land glaciers are all in the southwest (defined here as south of 65° N), a relatively temperate Greenland region , as compared to north Greenland. Intuitively, one might expect a general warming to cause glaciers in a temperate region to begin loosing mass prior to the glaciers in a polar region.

This supposition is supported by the fact that the magnitudes of the proportion of retreating glaciers is twice that of the more northerly sample, the marine terminating glaciers, discussed later. The rise in the proportion of land glaciers retreating between 1880 and 1940 mimics the rise in annual temperatures at the Ivigtut coastal station (Figure 1).

The abrupt drop in the proportion of retreating land terminating glaciers post-1940 is anti-correlated with the Ivigtut coastal temperature record, with surface air temperatures remaining elevated until the mid 1960s. This inconsistency is due either to errors in the terminus position data, front position changes caused by ice flow dynamics and not climate or some other climatic variable. Oerlemans (2005) convincingly shows that the length of a land glacier is primarily controlled by the local air temperature. Therefore, the cause of this inconsistency remains uncertain.

Marine Terminating Glaciers

The 54 marine terminating glaciers of the database are mainly located in West Greenland and the proportion of marine terminating glaciers retreating is shown in Figure 2b. The marine terminating glaciers appear to be stagnant until 1870 when the proportion retreating increased at a roughly constant rate over the next 80 years, with half of the sample glaciers retreating by 1950. After this maximum, the proportion of marine glaciers retreating declined until reaching 0.10 by 1980 and remaining low for the next ten years.

The proportion of marine terminating glaciers retreating over time is in general agreement with the climatic trends of Greenland. Recall that Greenland surface air temperatures were elevated from roughly 1929 to 1950 (Figure 1) and the maximum proportion of marine terminating glaciers retreating was in 1950. Despite the coarse resolution of the sample, there is a general concurrence between maximum annual surface-air temperature and the number of marine terminating glaciers retreating (Figures 1 and 2b). Before speculating on the causes of this agreement, I will inspect the length change records of some individual marine terminating glaciers having considerable temporal resolution.

Individual Marine Terminating Glacier Behavior

Four individual annual area change records and annual surface-air temperature anomalies (1880-1920 base period) from three different coastal stations are illustrated in Figure 3. These four glaciers are marine terminating and span the west Greenland coast from roughly 61° N to 77° N. A consistent feature among all four glaciers is the annual area changes appear to be greatest in relative magnitude sometime between 1920 and 1950. The actual patterns of annual area change, however, are otherwise quite different between the four glaciers. Before analyzing the individual glacier records further, I will discuss some generally accepted mechanisms of marine terminating glacier retreat.

The first mechanism will be referred to as the buttressing effect. If a glacier is floating at its front, then the lateral drag experienced by the ice tongue induces a resistive force on the grounded portion upstream (Patterson, 1994). If the floating portion were removed, then the resistive forces will go to zero and the grounded portion of the glacier can speed up, normally resulting in a retreat (Hughes, 1987; Scambos et al, 2004). This mechanism has been observed in Antarctica after the disintegration of the Larsen B ice shelf in 2002 (Scambos et al. 2004) and in Greenland at Jakobshavn Isbrae after the 11 km floating tongue collapse between 2000 and 2003 (Joughin et al. 2006).

The other retreat mechanism will be referred to as the buoyancy mechanism. If a glacier is grounded below sea level at its front and some perturbation causes it to float, then the glacier becomes decoupled form the resistive forces at the bed, causing it to accelerate and retreat (Meier and Post, 1987; Pfeffer, 2008). One possible mechanism causing a glacier to begin floating is persistent thinning until some threshold thickness minimum for floatation is reached, as observed on the Columbia glacier in Alaska (Pfeffer, 2008). Another way to cause floatation is retreat of the front over a reverse bed slope, which causes the threshold thickness for floatation to increase above the thickness of the glacier. Howat et al. (2008) have shown that the retreat of many glaciers in Southeast Greenland over the last five years is due to a slight retreat over a reverse bed slope.

Harald Moltke Bræ

Measurements compiled by J. W. Wright (1939) of Harald Moltke glacier in northwest Greenland indicate: a 1916-1926 retreat; a 1926-1932 advance; and a 1932-1936 retreat at a rate three times greater than in 1916-1926 (Figure 3a). The advance of 2 km between 1926 and 1928 corresponds to a minimum average surface velocity of 1.0 km y^{-1}, exceeding measurements of 0.03 km y^{-1} in 1937-1938 and 0.3 km y^{-1} in 1956 (Mock, 1966). After the 1926-1932 advance, the calving front retreated rapidly until a new stable position was reached by 1937. Besides a retreat sometime between 1953 and 1962, the calving front has been relatively invariant since the surge. More recently, however, Rignot and Kanagaratnam (2006) mentioned that another surge had begun at Moltke glacier in 2005.

An investigation the local climate during these surge events would shed considerable light on Moltke glacier dynamics. Unfortunately, the closest meteorological station spanning the times of interest is ~500 km to the south of Moltke glacier in Upernavik (Cappelan *et al.*, 2007). The spatial extent of the 1920s warming was continental in scale (Box et al., 2009), so some comparisons are appropriate. Upernavik annual temperatures rose 5°C between 1920 and 1928, with 1928 being the third warmest year on the entire 133 year record. The warmest annual temperature on record was in 1947 and does not coincide with any significant frontal variation of Harald Moltke glacier. The last ten years were notably warm in Upernavik, which includes the second warmest annual temperature on record in 2003. This recent warming trend was concurrent with the surge of Moltke glacier in 2005.

The rise in surface-air temperatures between 1920 and 1928 at Upernavik coastal station suggests a climatic cause of the 1926-1932 surging event. There is evidence of ice thinning in the vicinity of Moltke glacier during the 1930s (Wright, 1939). The local Inuit noticed the emergence of some nunataks during the 1930s. In addition, Wright is told of an icecap in the vicinity of Moltke glacier that vanished by 1923, suggesting that the ice may have began thinning prior to the surge of Harald Moltke glacier. Since we don't know whether the front of Moltke glacier was grounded or not prior to the surge, we can't speculate on specific retreat mechanisms. Nonetheless, our results provide good evidence that the surges of Harald Moltke glacier are a rapid response (1-10 years) to climate warming.

Upernavik Isstrøm

Figure 3b illustrates the 1886-1973 changes at the northwest Greenland Upernavik Isstrøm ice front and archipellago. The Upernaik glacier complex consists of multiple ice streams feeding what became the Upernavik Isfjord, producing one of the widest collective glacier fronts in Greenland (~27 km). Measurements compiled from Weidick (1958, 1995) and Zhou and Jezek (2002) illustrate a stagnant calving front until 1931, when it began a rapid retreat that peaked between 1942 and 1946 and ended by 1953. From 1953-1963 the front remained stationary, followed by retreat until the end of our time series.

Although Upernavik annual temperatures were anomalously warm during the rapid Upernavik glacier retreat between 1931 and 1947 (Figure 3b), the retreat was probably initiated by a succession of warm years from 1926 to 1931. Year 1928 was the third warmest year on the Upernavik coastal station record (see also Figure 1) and note that there is no significant change of the Upernavik calving front position in that year. I suggest that prolonged melting between 1926 and 1931 thinned the glacier until a threshold was reached and the glacier began its rapid retreat. Any further comment would be speculation due to lack of knowledge about the glaciers frontal state (floating or grounded). However, as Upernavik glacier began its retreat, it also had to overcome the resistive drag provided by the abundance of islands in its forebay. Recent measurements on Upernavik glacier suggest that its front is grounded and it is thinner than the threshold thickness for floatation, but the glacier has not began retreating perhaps due to resistive stresses provided by drag along its lateral margins (Pfeffer, 2007).

Jakobshavn Isbrae

Jakobshavn Isbrae, west Greenland is the most productive glacier in Greenland in terms of ice discharge (Rignot and Kanagaratnam, 2006). Its record of frontal variations shown in Figure 3c is the longest continuous record in Greenland (Weidick, 1995). Jakobshavn Isbrae glacier continuously retreated since its calving front position was first measured by Heinrich J. Rink in 1850 until the mid 20th century (Weidick and Bennike, 2007). A notable feature of its behavior is the rapid retreat between 1929 and 1931 (Figure 3c). A slight retreat continued until 1946, when the front retreated into a topographically controlled quasi-stable position between 1946 and 1998 (Sohn et al. 1998; Csatho et al. 2007). Between 2001 and 2007, the glacier retreated approximately 15 km, a collapse that exceeded the 1929-1931 retreat rate.

The frontal variations at Jakobshavn Isbrae are strongly related to annual temperature (Figure 3c). It has long been known that the Jakobshavn Isbrae is especially sensitive to the local climate (Weidick and Bennike, 2007 and references therein) and the cause of its breakup between 2001 and 2007 is no exception (Joughin et al. 2004). The mechanism responsible for the recent breakup is thought to be the buttressing effect caused by prolonged thinning (Hughes, 1987; Joughin et al. 2004). However, Csatho et al (2007) suggest that the glacier was grounded until at least 1946, and therefore the buttressing mechanism could not have been the cause of its sensitivity to climate prior to 1946. Whatever the mechanism of retreat prior to 1946 may have been, there is astounding coherence between elevated annual temperatures and the retreat of Ilulissat glacier between 1929 and 1931 (Figure 3c).

Arsuk Glacier

Arsuk Glacier is a relatively small (1 km wide) marine terminating glacier in southwest Greenland (Weidick, 1959). Besides a 200 m retreat between 1869 and 1871, the glacier retreated only slightly between 1862 and 1908 (Figure 3d). From 1908 until the end of the record in 1955, Arsuk glacier began a more intense trend of retreat, with the greatest retreat rate occurring between 1923 and 1928.

Arsuk glacier front fluctuations appear to be responsive to local surface air temperatures (Figure 3d). The Ivigtut meteorological station is located ~15km southwest of Arsuk glacier, and was in operation from 1873 to 1966 (Cappelen *et al.*, 2007). A period of climate warming started with the first annual temperature exceeding 2°C in 1915 and by 1928 there were already four years that exceeded 2°C. It seems that the calving front began retreating more intensely post 1908 and I speculate the reason to be increased melt forced by this warming trend.

Kangerdlugssuaq Glacier

Kangerdlugssuaq glacier is the most productive east Greenland glacier; and on occasion is the most productive Greenland glacier (Rignot and Kanagaratnam, 2006). The first (non-native) historical observation of Kangerdlugssuaq glacier was made in late August of 1930 by the British Arctic Air Route Expedition (Chapman, 1932, p. 27-52). They observed the glacier to have a long tongue extending about 5 km out of its embayment (Figure 4). The Kangerdlugssuaq glacier was visited again in August 1932 by Ejnar Mikkelsen, who noted that the tongue is not a continuation of the inland ice, as thin fractures apparently separate it from the glacier (Mikkelsen, 1933). An oblique aerial photograph from the Seventh Thule Expedition in the summer of 1933 showed that this tongue had completely vanished from the vicinity of the calving front (Figure 5; Gabrel-Jørgensen, 1933). These fortuitous observations document an extremely large ice discharge and retreat.

A relationship may exist between the massive discharge of ice at Kangerdlugssuaq around 1930 and the local climate. During his visit in 1932, Ejnar Mikkelsen noticed that large glaciers along the east coast of Greenland had vanished since his first visit in 1900 and considered this "definite proof that the climate has altered and become milder" (Mikkelsen, 1933). The Tasiilaq meteorological station (Cappelen *et al*., 2007), located ~350 km south of Kangerdlugssuaq, confirms Mikkelsen's intuition by recorded its first above freezing annual temperatures in 1928, 1929 and 1931 since it began operating in 1895. I speculate that this warm temperature trend is linked to the production of the massive iceberg at Kangerdlugssuaq glacier observed between 1930 and 1932.

Conclusions

My review of the literature pertaining to the historical fluctuations of Greenland glaciers allowed the construction of an aggregate of snapshots of glacier changes in Greenland over the last century-plus. These aggregated snapshots suggest that the time period between 1920 and 1950 was analogous to the retreating status of many Greenland glaciers today. Our hypothesis that *there was an accelerated retreat of Greenland glaciers in response to the 1920s warming period* is not rejected due to essentially no contradictory findings and a variety of information supporting my hypothesis. Of the four glaciers with sufficient resolution to test our hypothesis, all of them appeared to intensify their retreat in the 1920s. Current mechanisms of tidewater glacier retreat are consistent with the four length change records, adding credence to the buttressing and buoyancy mechanisms. There is still much more that can be done to increase the sample size and resolution of the glacier length change database from Greenland. The entire collection of aerial photographs from the British Arctic Air Route Expedition of 1930/1931 have yet to be analyzed for glacial variations during this exceptionally warm time period in Greenland and this would substantially increase our understanding of the history of Greenland glacier behavior.

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Figures

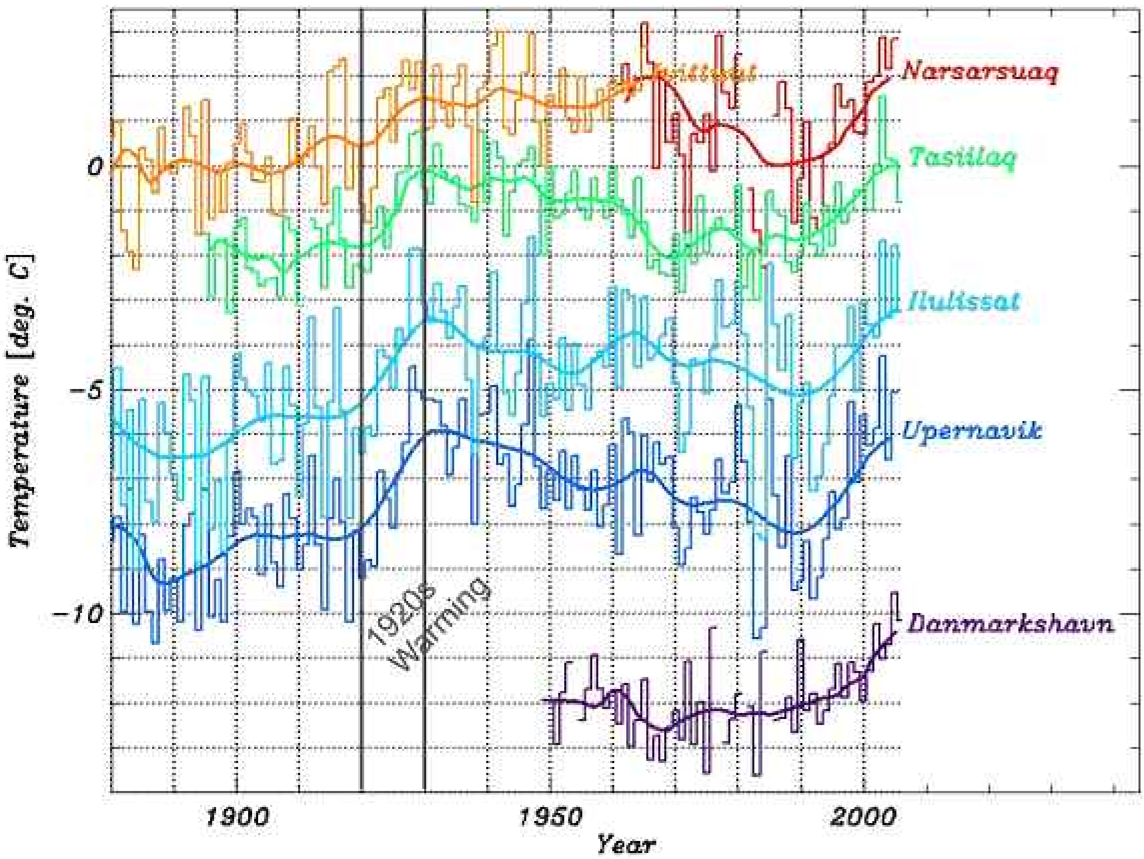

Figure 1. Annual surface air temperature anomalies (1880-1920 base period) and ten year running averages from coastal stations around Greenland. From the Cappelen et al. (2007) dataset.

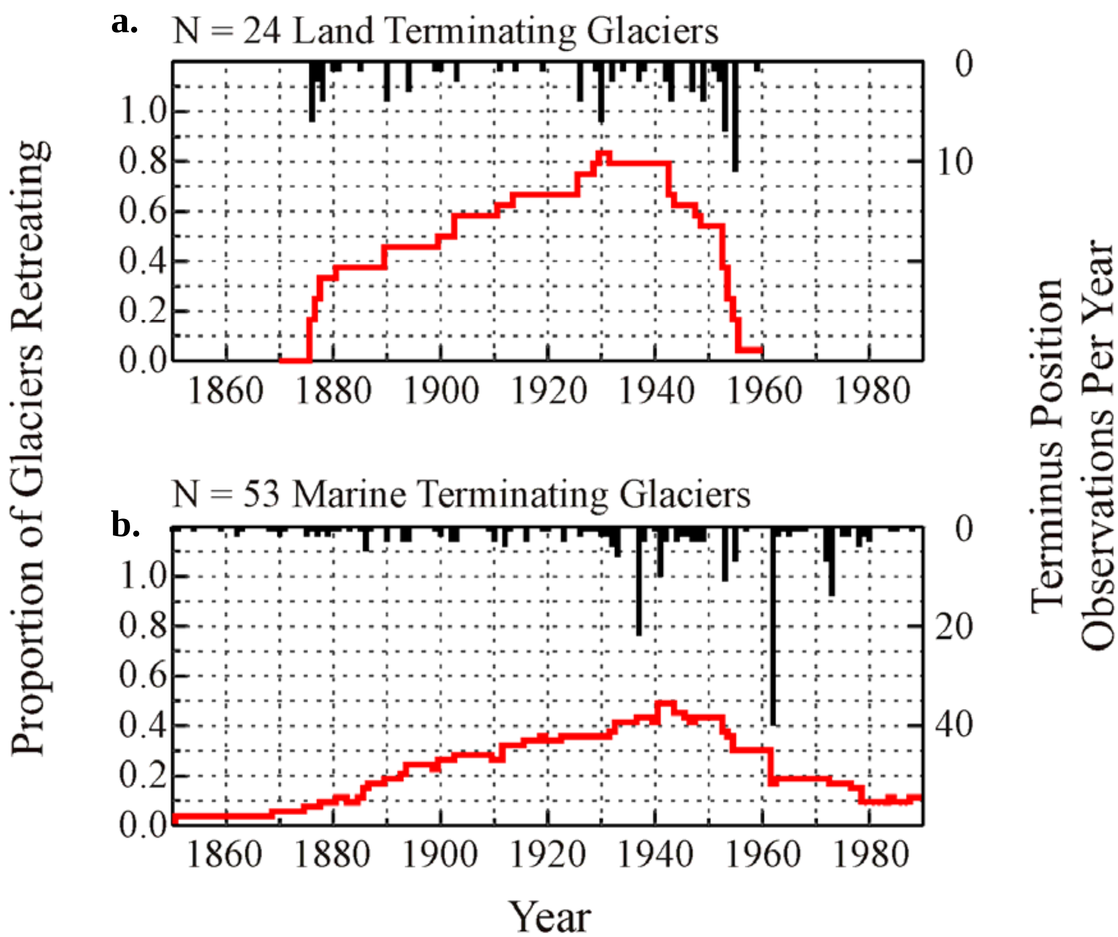

Figure 2. Time series of the proportion of (a) land terminating and (b) marine terminating glaciers retreating. The vertical black bars indicate the number of terminus position observations per year used to interpolate an annual resolution of the sample time series.

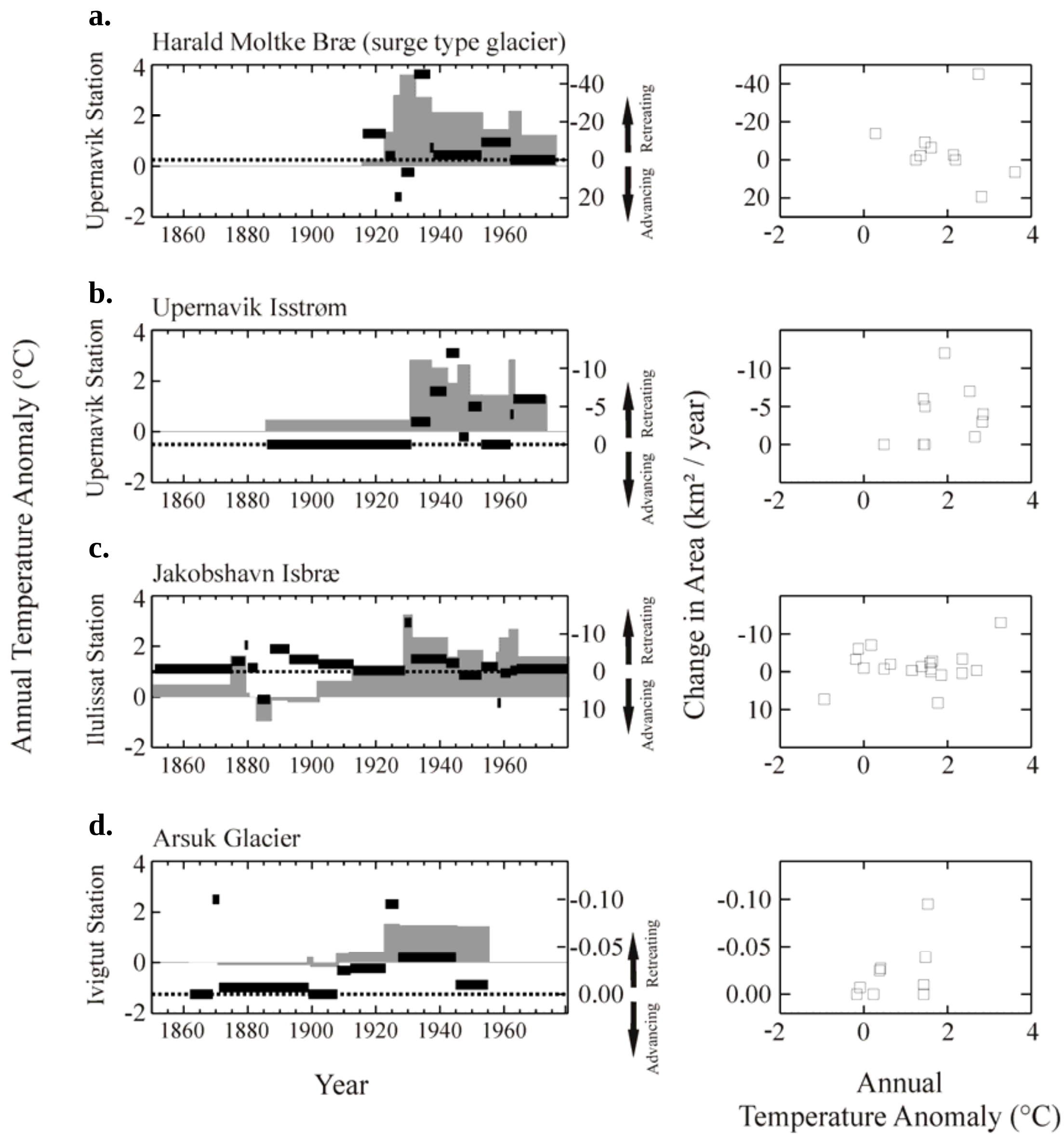

Figure 3. (Left column) annual area change time series for individual glaciers (black bars) and annual surface air temperature anomalies (1880-1920 base period) from the closest meteorological station to the respective glacier (vertical grey bars). (Right column) each glacier time series is accompanied by a plot of annual temperature anomaly vs. annual area change.

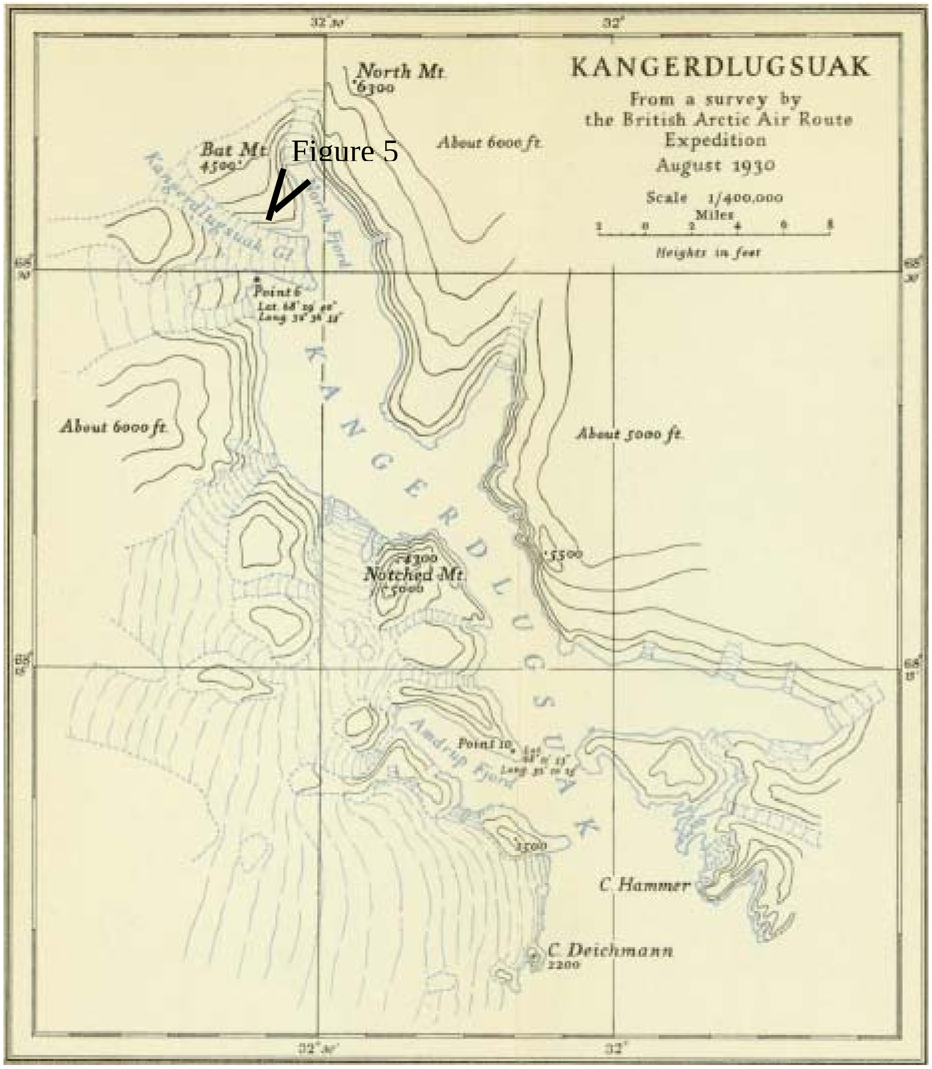

Figure 4. Map from the British Arctic Air Route Expedition showing the extent of the large ‘tongue’ of Kangerdlugssuaq in 1930 (Figure from Watkins et al, 1932).

Figure 5. Oblique aerial photograph from the Seventh Thule Expedition in 1933 showing that the calving front of Kangerdlugssuaq is not connected to the massive ‘tongue’ shown in Figure 4. Approximate location of photograph is given in Figure 4 (Photograph from Gabrel-Jørgensen, 1933).

Tables

Year	Type	Source
1933	Map, Documentary	Gabrel-Jorgensen [1933]
1928	Map, Documentary	Koch [1928]
1933	Map, Documentary	Mikkelsen [1933]
1932	Map, Documentary	Watkins et al. [1932]
1939	Map, Documentary	Wright [1939]
1948+	Map	US Army Map Service [1957]
1800+	Publication	Weidick [1958; 1959; 1968; 1994; 1995]
1962-1962	Satellite	Zhou and Jezek [2002]

Table 1. List of data sources used to compile the length change database.

Glacier Name	T0	S0	T1	S1	T2	S2	T3	S3	T4	S4	T5	S5	T6	S5	T6
Marie Sophie	1949	-1.00	1962	1.00	1978	2.00	2	2.00	2	2.00	2	2.00	2	2.00	2
Academy	1912	-1.00	1949	1.00	1963	-1.00	1978	2.00	2	2.00	2	2.00	2	2.00	2
Knud Rasmussen	1938	0.00	1962	-1.00	1976	2.00	2	2.00	2	2.00	2	2.00	2	2.00	2
Chamberlin	1923	-1.00	1937	0.00	1962	2.00	2	2.00	2	2.00	2	2.00	2	2.00	2
Ussing Braeer	1886	0.00	1941	-4.50	1962	0.00	1975	0.00	2000	0.00	2005	2.00	2	2.00	2
Giesecke	1886	-3.00	1941	-2.00	1962	0.00	1975	0.00	2000	0.00	2005	2.00	2	2.00	2
Nunatakavasaup sermia	1886	0.00	1941	0.00	1973	0.00	2000	0.00	2005	0.00	2	2.00	2	2.00	2
Alangorssup sermia	1886	0.00	1941	0.00	1973	0.00	2000	0.00	2005	0.00	2	2.00	2	2.00	2
Umiamako	1944	0.00	1957	0.00	1973	-1.00	2000	-2.00	2005	2.00	2	2.00	2	2.00	2
Rinks	1937	0.00	1962	0.00	1973	0.00	2000	0.00	2005	2.00	2	2.00	2	2.00	2
Kangerdlugssup Sermerssua	1937	0.00	1962	0.00	1973	0.00	2000	2.00	2	2.00	2	2.00	2	2.00	2
Kangerdluarssup Sermia	1937	-1.00	1962	0.00	1973	0.00	2000	0.00	2005	2.00	2	2.00	2	2.00	2
Qaumarujuk	1929	-1.00	1932	-1.00	1949	-1.00	1953	-1.00	1959	-1.00	1967	2.00	2	2.00	2
Perdlerfiup Sermia	1937	0.50	1962	0.00	1973	0.00	2000	-0.50	2005	2.00	2	2.00	2	2.00	2
Sermeq Silardleq	1937	0.00	1962	0.00	1973	1.20	2000	-1.00	2005	2.00	2	2.00	2	2.00	2
Kangigdleq	1937	0.00	1962	0.00	1973	0.00	2000	0.00	2005	2.00	2	2.00	2	2.00	2
Sermilik	1937	0.00	1962	0.00	1973	0.00	2000	0.00	2005	2.00	2	2.00	2	2.00	2
Sermiarssuit	1893	-1.00	1953	2.00	2	2.00	2	2.00	2	2.00	2	2.00	2	2.00	2
Lille Gletscher	1937	0.00	1962	0.00	1973	0.00	2000	-0.30	2005	2.00	2	2.00	2	2.00	2
Qarassup (Store)	1879	0.00	1937	0.00	1962	0.00	1973	0.00	2000	0.00	2005	2.00	2	2.00	2
Torsukatat (avangnardleq)	1902	0.00	1937	0.00	1962	0.00	1980	0.00	2000	0.00	2005	2	2	2.00	2
Torsukatat (kujatdleq)	1902	0.00	1937	-1.50	1962	0.00	1980	0.00	2000	0.00	2005	2	2	2.00	2
Kangilerngata Sermia	1937	0.00	1962	0.00	2000	-1.00	2005	2.00	2	2.00	2	2.00	2	2.00	2
Eqip Sermia	1893	0.00	1910	0.00	1941	-2.00	1962	0.00	2000	-0.40	2005	2.00	2	2.00	2
Sermeq Avangnardleq (Kangilerngata)	1870	0.00	1885	-1.50	1920	0.00	1941	1.60	1984	-4.00	2000	0.00	2005	2.00	2
Alangordliup Sermia	1870	1.00	1910	0.00	1937	0.00	1962	0.00	2000	0.00	2005	2.00	2	2.00	2
Sarqardliup Sermia	1875	-1.20	1910	0.00	1937	0.00	1962	0.00	2000	0.00	2005	2.00	2	2.00	2
Kangerdlugssuaq	1909	1.00	1930	0.00	1932	-9.00	1933	0.00	1937	0.00	1962	0.00	1966	2.00	2
Nordenskiolds	1916	0.00	1941	0.00	1962	1.00	2000	0.00	2005	2.00	2	2.00	2	2.00	2

Usudglup Sermia	1890	0.00	1900	-1.20	1940	0.00	1941	-4.00	1944	4.00	1962	0.00	2000	0.00	2005
Glacier de France	1933	-1.00	1962	1.00	1972	2.00	2	2.00	2	2.00	2	2.00	2	2.00	2
Midgard	1933	-5.00	1968	-10.00	1972	-1.00	1978	2.00	2	2.00	2	2.00	2	2.00	2
Fenris	1912	-1.00	1933	-3.00	1972	2.00	2	2.00	2	2.00	2	2.00	2	2.00	2
Helheim	1933	0.00	1941	1.00	1972	-1.00	1978	2.00	2	2.00	2	2.00	2	2.00	2
Karale	1933	-4.50	1972	1.00	1973	2.00	2	2.00	2	2.00	2	2.00	2	2.00	2
Ujaragssuit	1840	999.00	1885	2.00	1930	0.00	1934	0.00	1937	0.00	1942	0.00	1955	0.00	1962
Narssap Sermia	1903	0.00	1916	0.00	1930	0.00	1937	0.00	1942	0.00	1955	0.00	1962	0.00	2000
Qamanarssup Sermia	1937	0.00	1942	0.00	1962	0.00	2000	0.00	2005	2.00	2	2.00	2	2.00	2
Kangersuneq	1808	-6.00	1850	0.00	1903	-4.00	1932	0.00	1937	0	1941	-2	1944	0.5	1948
Sadlen Glaciers	1914	-0.30	1930	-0.10	1955	2.00	2	2.00	2	2.00	2	2.00	2	2.00	2
Sermilik [2]	1878	0.00	1930	0.00	1955	0.00	1962	0.00	2000	0.00	2005	2.00	2	2.00	2
The Kitdlavat Glaciers	1878	-0.10	1930	-0.15	1955	2.00	2	2.00	2	2.00	2	2.00	2	2.00	2
Nakaissorssuaq	1859	0.00	1878	-2.09	1948	0.00	1962	2.00	2	2.00	2	2.00	2	2.00	2
Kangarssuk, Frederikshaab Isblink	1878	-0.30	1947	2.00	2	2.00	2	2.00	2	2.00	2	2.00	2	2.00	2
Davisstraedet, Frederikshaabs Isblink	1894	0.00	1930	-0.15	1952	2.00	2	2.00	2	2.00	2	2.00	2	2.00	2
Itivdleq (Majorarissat), Frederikshaabs Isblink	1878	0.00	1930	2.00	2	2.00	2	2.00	2	2.00	2	2.00	2	2.00	2
Avangnardleq, Kvanefjord	1785	999.00	1809	-0.20	1955	0.00	1962	2.00	2	2.00	2	2.00	2	2.00	2
Akugdleq, Kvanefjord	1877	-999.00	1919	-999.00	1955	0.00	2000	0.00	2005	2.00	2	2.00	2	2.00	2
Nigerdlekasik, Kvanefjord	1785	999.00	1868	0.00	1877	0.00	1919	-0.50	1955	0.00	1962	0.00	2000	-0.40	2005
Ukassorssuaq (Sermilik, Narssalik)	1862	999.00	1877	3.00	1948	-0.70	1962	0.70	2000	0.00	2005	2.00	2	2.00	2
Sermiligarssuk Brae	1955	0.00	1962	0.00	2000	0.00	2006	2.00	2	2.00	2	2.00	2	2.00	2
Sioralik	1877	-0.30	1955	0.00	1962	-0.60	2000	-0.20	2006	2.00	2	2	2	2.00	2
Eqalorutsit kangigdlit sermia	1894	0.00	1932	0.00	1947	0.00	1953	0.00	1955	0.00	1962	2.00	2	2.00	2
Eqalorutsit kitdlit sermiat, east	1894	-1.50	1947	-0.50	1953	0.00	1962	2.00	2	2.00	2	2.00	2	2.00	2
Qorqup Sermia (Qoroq)	1876	0.00	1926	-5.00	1953	0.00	1962	2.00	2	2.00	2	2.00	2	2.00	2
Eqalorutsit kitdlit sermiat, west	1894	-3.50	1953	0.00	1962	2.00	2	2.00	2	2.00	2	2.00	2	2.00	2
Kiagtut sermia	1876	-0.10	1899	-999.00	1953	2.00	2	2.00	2	2.00	2	2.00	2	2.00	2
Nordre Qornoq	1890	0.00	1903	-0.60	1949	-0.03	1951	-0.01	1955	2.00	2	2.00	2	2.00	2
Kangerdluarssuk, East	1876	-2.50	1953	0.00	1962	2.00	2	2.00	2	2.00	2	2.00	2	2.00	2
Nordre Qipisarqo Brae	1890	-999.00	1943	0.00	1947	2.00	2	2.00	2	2.00	2	2.00	2	2.00	2
Sordre Qipisarqo Brae	1890	-999.00	1943	0.00	1947	0.00	1955	2.00	2	2.00	2	2.00	2	2.00	2

Sondre Qornoq	1880	0.04	1890	0.00	1903	-0.60	1938	-0.10	1949	0.00	1955	2.00	2	2.00	2
Kangerdluarssuk, center	1876	-0.03	1953	0.00	1955	2.00	2	2.00	2	2.00	2	2.00	2	2.00	2
Sondre Qornoq (2)	1809	0.00	1903	0.00	1938	2.00	2	2.00	2	2.00	2	2.00	2	2.00	2
Kangerdluarssuk, west	1876	-1.00	1953	0.00	1962	2.00	2	2.00	2	2.00	2	2.00	2	2.00	2
Qaleragdlit fjord	1890	0.00	1912	-4.50	1953	0.00	1962	2.00	2	2.00	2	2.00	2	2.00	2
Jespersen	1911	-0.50	1926	-0.75	1953	2.00	2	2.00	2	2.00	2	2.00	2	2.00	2
Sermitsialik	1854	0	1890	-0.7	1947	0	1953	-0.35	1965	-0.4	1967	-0.3	1979	-0.15	1980
Kujatleq valley glacier	1926	-999.00	1953	2.00	2	2.00	2	2.00	2	2.00	2	2.00	2	2.00	2
Narssaq glacier	1853	0.00	1900	-999.00	1932	2.00	1952	0.00	1955	2.00	2	2.00	2	2.00	2
Sermeq in Sondre Sermilik	1820	999.00	1881	-1.00	1945	-2.00	1953	-3.00	1962	-5.00	1972	-3.00	1973	1.00	1979
Sermeq in Tasermiut	1876	0.00	1881	-0.80	1894	0.00	1926	-0.80	1943	0.00	1949	2.00	2	2.00	2
Sermitsiaq in Tasermiut	1876	0.00	1894	-0.40	1926	-0.40	1943	2	2	2.00	2	2.00	2	2.00	2

Table 2. Length change database for 77 glaciers in Greenland compiled from the sources in Table 1. The notation ‘T(n)’ refers to the year of observation and ‘S(n)’ refers to the change in length of the glacier between years T(n) and T(n+1) in km. The arbitrary value ‘2’ is assigned to cells without data.